Mechanism of brightness enhancement in multimode LD-pumped graded-index fiber Raman lasers

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Abstract: A theory describing experimental beam profiles of multimode fiber Raman lasers is developed: random mode coupling, Kerr self-cleaning and spatial filtering play a decisive role in shaping Stokes beams, whereas depleted pump beams remain insensitive.
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1. Introduction

The Raman beam cleanup (RBC) effect was first demonstrated in 1979 by Andreev et al. [1], and provided an effective solution for the improvement of both quality and brightness of high-power solid-state or excimer laser beams at their Raman conversion in gaseous [1] or solid-state [2] media. This idea was further applied to Raman lasers based on a multimode fiber, in which low-quality multimode pump radiation is converted into a high-quality Stokes beam [3]. A previous analysis of pump and Stokes modes overlap integrals [4] has shown that the RBC effect is present in graded-index fibers, where lower-order Stokes modes have higher Raman gain for random pump launching conditions. Whereas in step-index fibers all transverse modes have nearly the same Raman gain. The available analysis of small-signal gain remains only qualitative, and it is not applicable to multimode fiber Raman lasers [3], where pump-to-Stokes conversion occurs within the cavity, and a strong signal is generated.

Recently, Raman lasers based on graded-index (GRIN) fibers have attracted a great deal of attention by providing the opportunity of an efficient Raman conversion of highly-multimode (M^2~30) radiation from high-power laser diodes (LDs) into a high-quality (M^2~2) Stokes beam. This approach is implemented in the all-fiber scheme with in-fiber fiber Bragg grating (FBG) cavity and fiber coupling of the LD pump radiation, see [5] for a review. Using commercially available GRIN fibers and 9xx-nm LDs, such Raman lasers may generate high-quality radiation at wavelengths <1 μm, where emission by conventional singlemode Yb-doped fiber lasers is hardly possible. By connecting several high-power LDs to a GRIN fiber with 100-μm core through a multimode 100-μm fiber pump combiner, allows for increasing the coupled pump power up to ~200W in this scheme, and to generate Stokes radiation with output powers 50-60 W at wavelengths 954 [5] and 976 [6] nm by using 915 and 940 nm LDs, respectively. Herewith, the optimization of the transverse profile of FBGs inscribed by femtosecond point-by-point technique in the near-axis part of the GRIN core enables a better spatial filtering effect, and allows for improving the Stokes beam quality to $M^2<2$ without any loss of conversion efficiency, thus providing a pump-to-Stokes brightness enhancement factor >70 [6]. Besides, measurements of output beam profiles [6] show a strong depletion of the pump beam, with burning of a hole that is much broader than the Stokes beam profile. At the same time, the developed analytical model on the base of radially-dependent balance equations [6] does not describe neither the beam profiles nor the brightness enhancement that are observed in experiments.

Here we perform numerical simulations by using a system of equations based on the coupled mode model, which takes into account both Raman and Kerr nonlinearity, random mode coupling and spatial filtering, for describing the propagation of pump and Stokes beams inside GRIN fiber cavity, and successfully compare the theoretical predictions for beam profiles with the experimental observations.

2. Results and discussion

We consider a scheme corresponding to the experiment reported in Ref. [6]. In our experiments, pump radiation from three fiber pigtailed high-power LDs operating at the wavelength of ~940 nm is added together by means of a 3x1 multimode fiber pump combiner. The input ports of the fused pump combiner are made of multimode step-index fiber with 105-μm core, and the output port is made of a 100-μm core GRIN fiber with a numerical aperture of 0.29. This fiber is spliced to the same 1-km-long 100-μm core GRIN fiber where Raman gain is provided by LD pumping. The linear laser cavity for the 1st Stokes wave is formed by a high-reflective (~90%) UV-inscribed FBG and an output low-reflective (~4%) fs-inscribed FBG, providing cavity feedback at the Stokes wavelength of 976 nm. The output FBG manifests spatial filtering properties with 10 dB lower reflection coefficient for higher order modes (≤0.4%). The output Stokes and residual pump beams were measured by a Thorlabs M^2 meter, and by using an appropriate spectral filters to select the corresponding wavelength.

For the simulation of beam profiles, we used a coupled-mode model which was initially developed for modeling the Kerr self-cleaning effect in the propagation of high-intensity sub-nanosecond pulses in GRIN fibers. The model takes into account the presence of random mode coupling [7], and it has been modified in accordance with the present experiments for the CW LD-pumped GRIN-fiber Raman laser. Specifically, the Raman effect was included, and we computed the dynamics of Stokes beam formation and propagation together with pump depletion in a lossy GRIN fiber (~2.6 dB as in experiment). Spatial filtering at each round trip was introduced, in order to take into account the experimental fs-FBG reflection (4% for fundamental mode, 0.4% for high-order modes).

Simulated and experimental beam profiles are compared in Fig.1(a,b) in absolute intensity units (W per square micron) within the GRIN fiber core of 100 μm diameter: here we can see the input pump beam (blue), the attenuated pump beam without depletion (dashed), the depleted output pump beam (black), and the generated Stokes beam (red). The comparison between experiments and simulations shows a very good agreement, both in the amplitude and in the shapes of the beams. Our simulations have revealed that random mode coupling in GRIN fibers leads to a parabolic pump beam shape, with a broadening of the hole burnt due to the pump depletion. Moreover, random coupling also greatly broadens and reduces the intensity of the Stokes beam, whereas Kerr self-cleaning and spatial filtering effects enhance both the intensity and beam quality of the Stokes wave so that a high brightness enhancement factor at pump-to-Stokes conversion is obtained. At the same time, the depleted pump beam profiles remain always nearly insensitive to the different physical effects. A more detailed comparison between theory and experiments, confirming these conclusions, will be presented at the conference.

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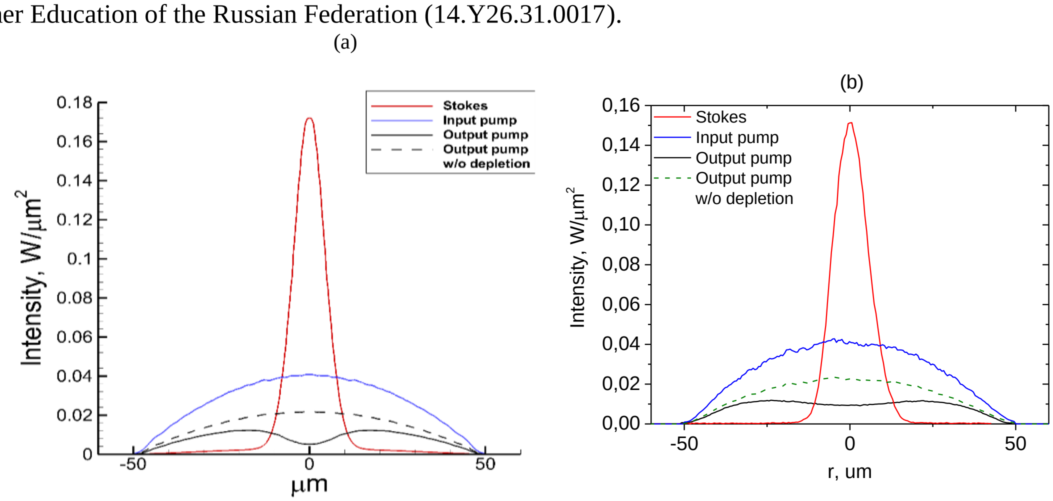

Fig.1. Theoretical (a) and experimental (b) profiles for the input, attenuated and depleted pump beam and corresponding Stokes beam generated in GRIN fiber with FBGs at ~155 W input pump power.

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